Queen Mary
University of London
Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 14

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Last revised 19 March 2020

What is this lecture about?

- Scintillators
  - Basic principles
  - Important materials in current use
  - Light detection
  - Low energy applications (gamma spectroscopy, medicine)
  - High energy applications (calorimeters, Time-of-flight)

Key points from previous lecture

- The photomultiplier is a vacuum photodetector which uses the external photoelectric effect (photocathode) and then secondary electron emission (dynodes) to provide a large area, fast, high gain sensor with low capacitance.
- Photosensitive areas up to several hundred cm^2 are available.
- Gains in excess of 10^6 obtainable.
- Low dark counts and limited sensitivity to temperature.
- Low QE compared to silicon devices, poor response in the red and near-IR regions.
- Bulky and somewhat fragile (especially large tubes), sensitive to helium ingress.
- Very few manufacturers available.

Non-linear response

Real scintillators show non-linearity of response as a function of gamma-ray energy.

This can be (must be) calibrated out in terms of the energy scale effect but it will generate non ideal resolution effects. Note that the sign of the non linearity (relative to normalisation at a few MeV) depends on the material of the scintillator

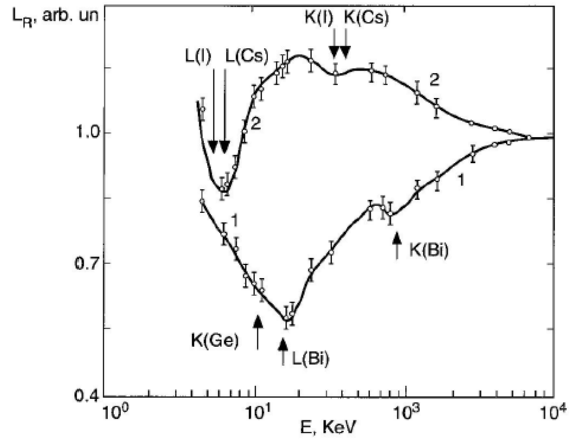


FIGURE 1.13 Scintillation response curves for BGO (1) and CsI:Tl (2) crystals. (From Averkiev, V. V. et al., *Pribory Tekh. Eksp.*, 4, 80, 1990.)

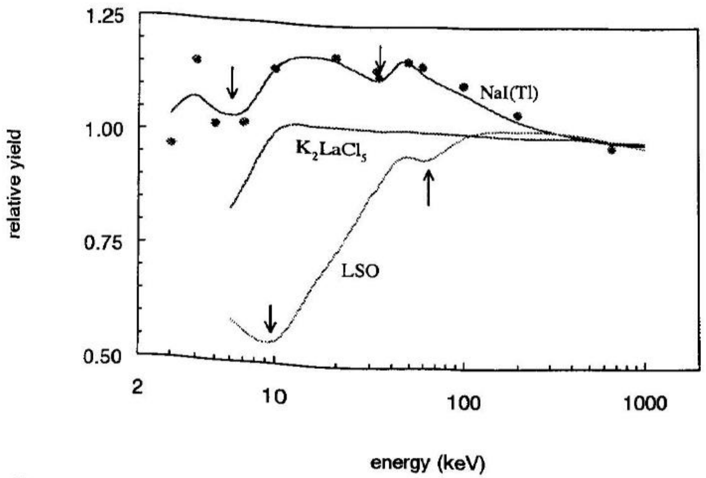


Figure 1: Response curves of $NaI(Tl^+)$, $Lu_2SiO_5(Ce^{3+})$(LSO), and $K_2LaCl_5(Ce^{3+})$, normalized to unity at E_γ=662 keV. The experimental data points, not shown in the Figure, for $NaI(Tl^+)$ can be found in [3]. For $K_2LaCl_5(Ce^{3+})$ and $Lu_2SiO_5(Ce^{3+})$ see [5]. The data points are results from Monte Carlo simulations of the scintillation process in $NaI(Tl^+)$. The arrows show the position of K-shell and L-shell binding energies.

Gamma ray interactions

Remember that gamma rays interact via

1. photoelectric effect
2. Compton scattering (inelastic scattering)
3. pair production (threshold at 1.02 MeV photon energy)

This means that the response of a finite sized scintillator to a monochromatic source of "low energy" photons (less than about 10 MeV) will be complex.

1. Photoelectric absorption: Primary photon is absorbed and a secondary electron with energy equal to the primary photon energy minus the binding energy of the electron.

We thus expect a single peak in the response of the scintillator (neglecting any escape X-rays).

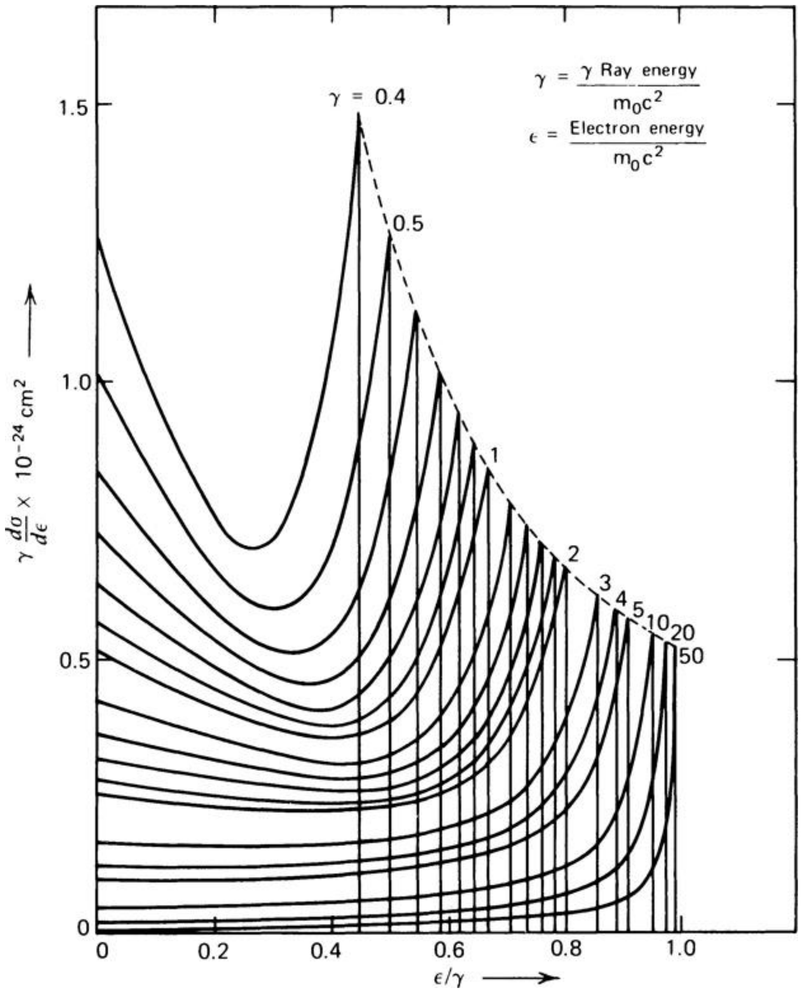
Gamma ray interactions

2. Compton effect: Inelastic scattering producing a free electron and a photon of lower energy than the original.

We thus expect a distribution in electron energies in the scintillator up to a kinematic limit.

Note that as the photon energy becomes much greater than the electron rest mass, the "Compton edge" approaches the incident photon energy.

This diagram assumes the electron that takes part in the interaction is free, binding energy effects can be significant.



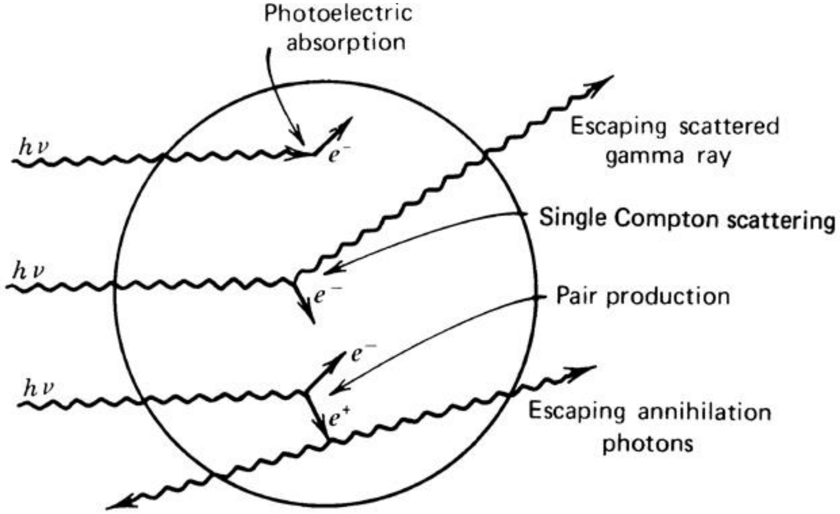
Gamma ray interactions

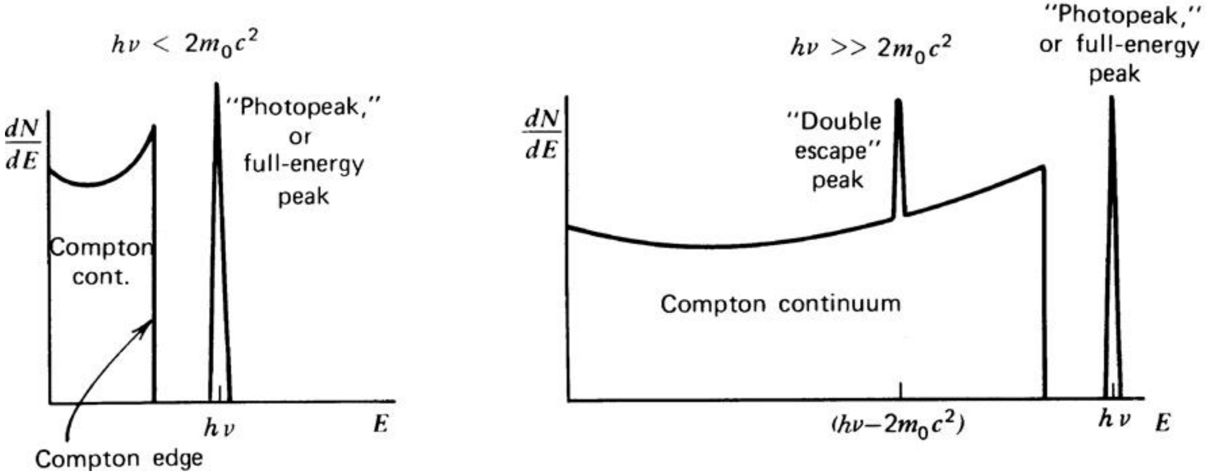
3. Pair production: When the photon energy is greater than twice the electron rest mass an electron/positron pair can be produced. Above about 10 MeV (most materials) this is the dominant process. In most scintillators the e+ or e- will travel only a few mm.

We thus expect a single peak in the spectrum of charged particle energy located at $2m_0c^2$ below the photon energy.

Note that the positron will annihilate with an electron in the scintillator to produce two 511 keV energy photons. One or both of these can escape from a small scintillator adding to the complexity of the spectrum.

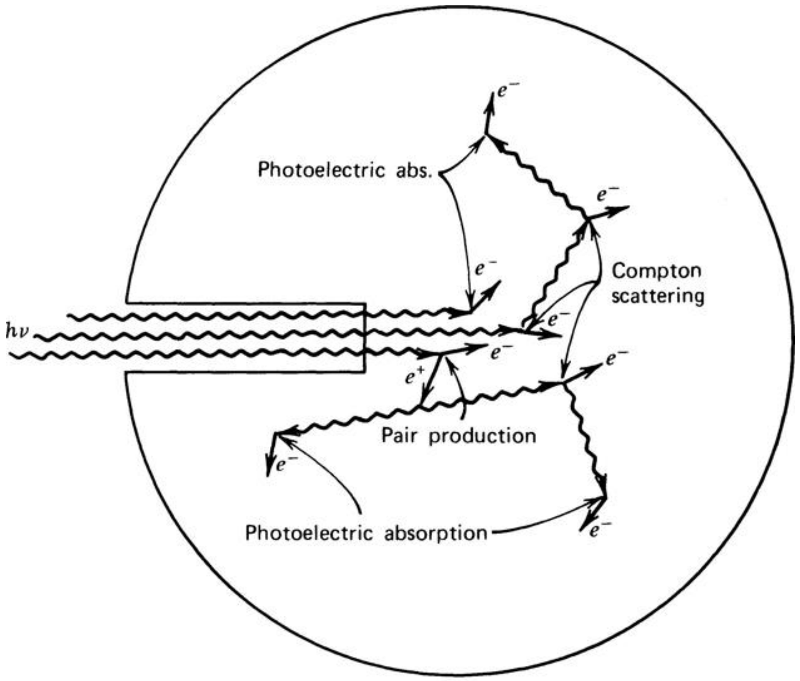
Small detectors

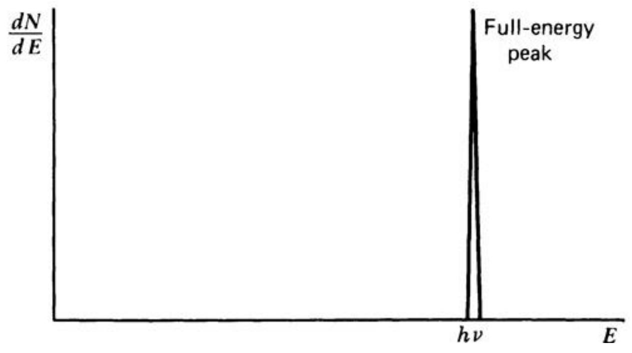




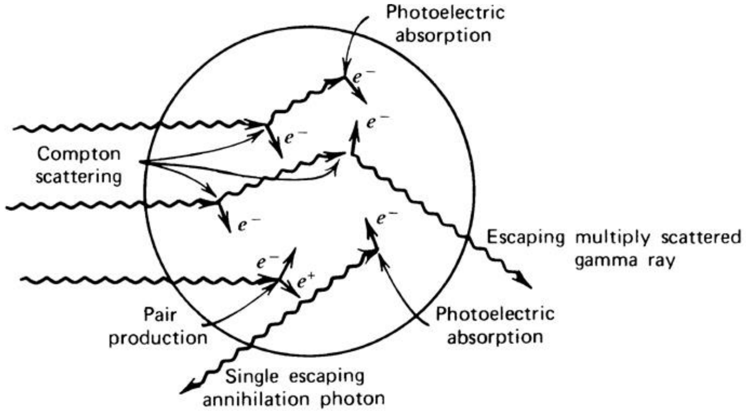
Large detectors

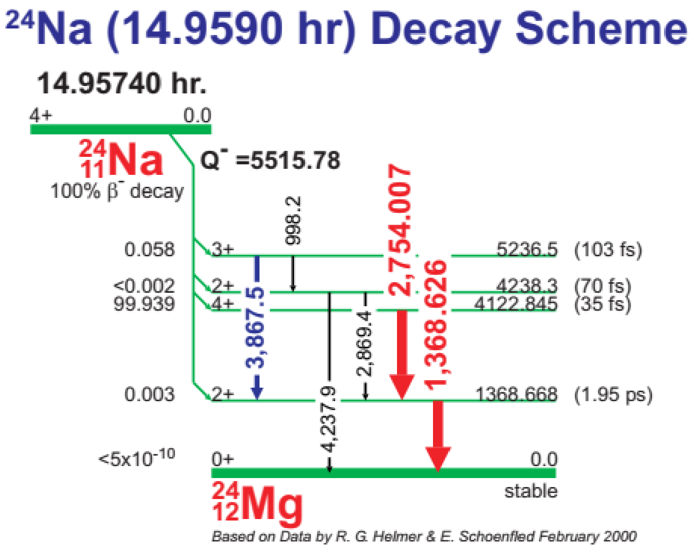
It isn’t going to be quite as good as this, some backscatter out of the detector where the radiation enters is likely.

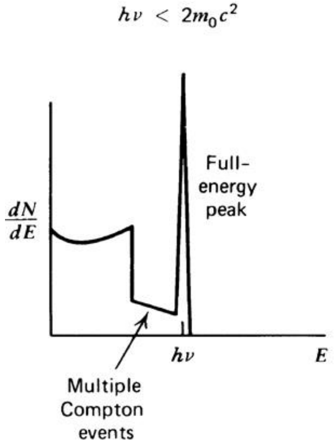


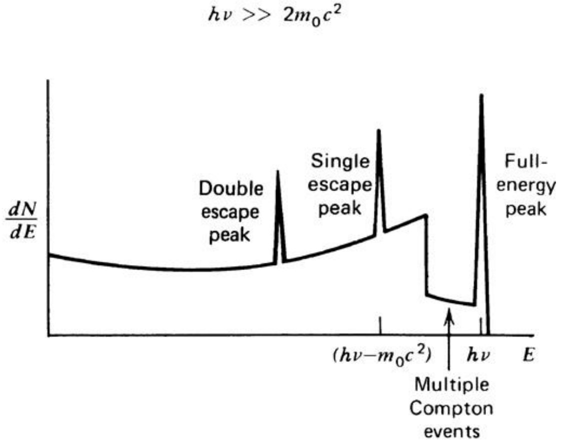


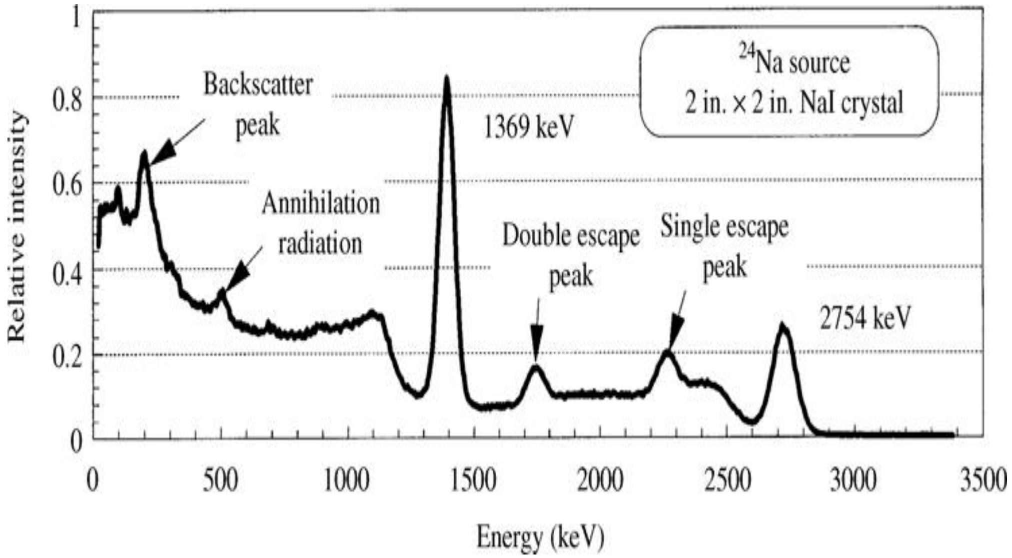
Intermediate detectors





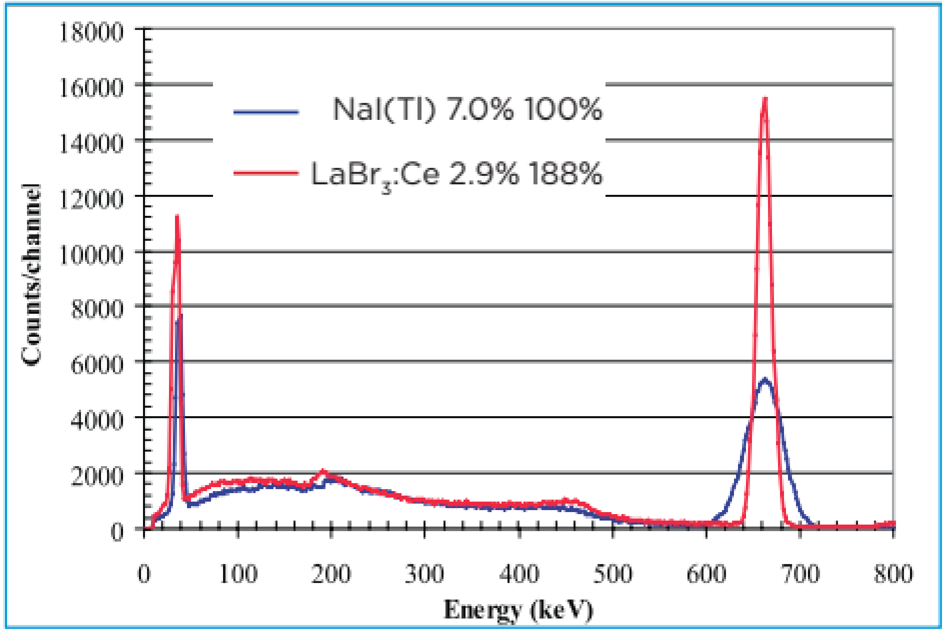




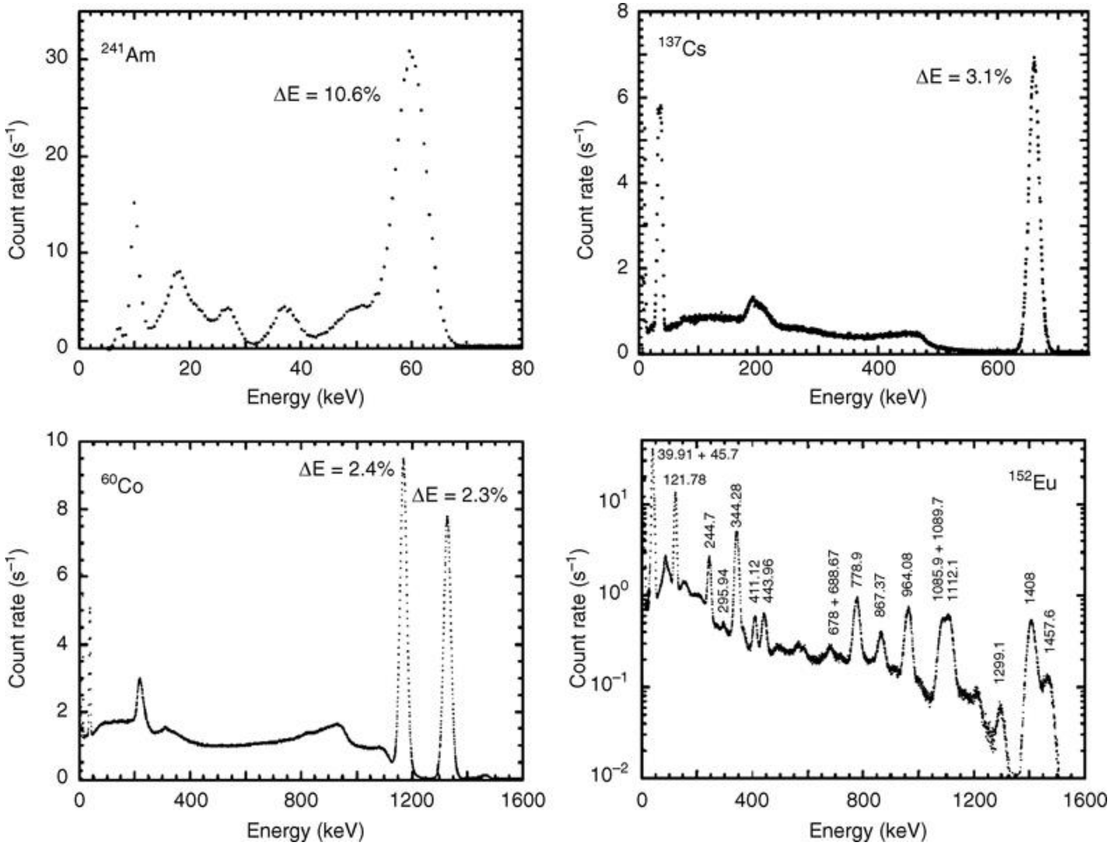


Gamma ray spectroscopy

5×5 cm $LaBr_3$(Ce) scintillator and ^{137}Cs (662 keV)



CRYSTALS SAINT-GOBAIN



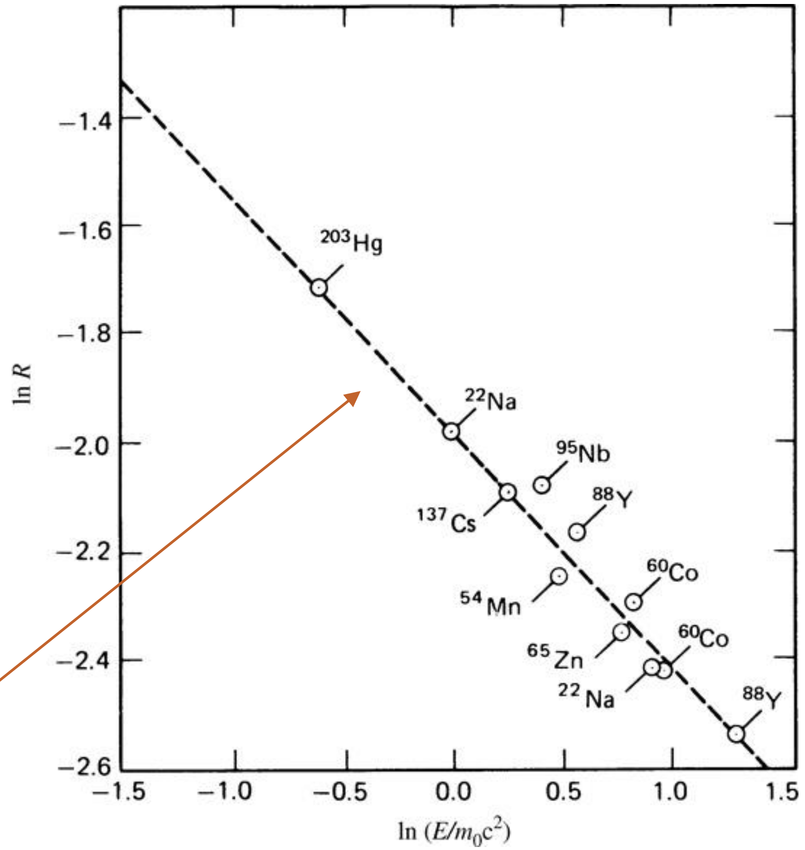
Gamma ray spectroscopy

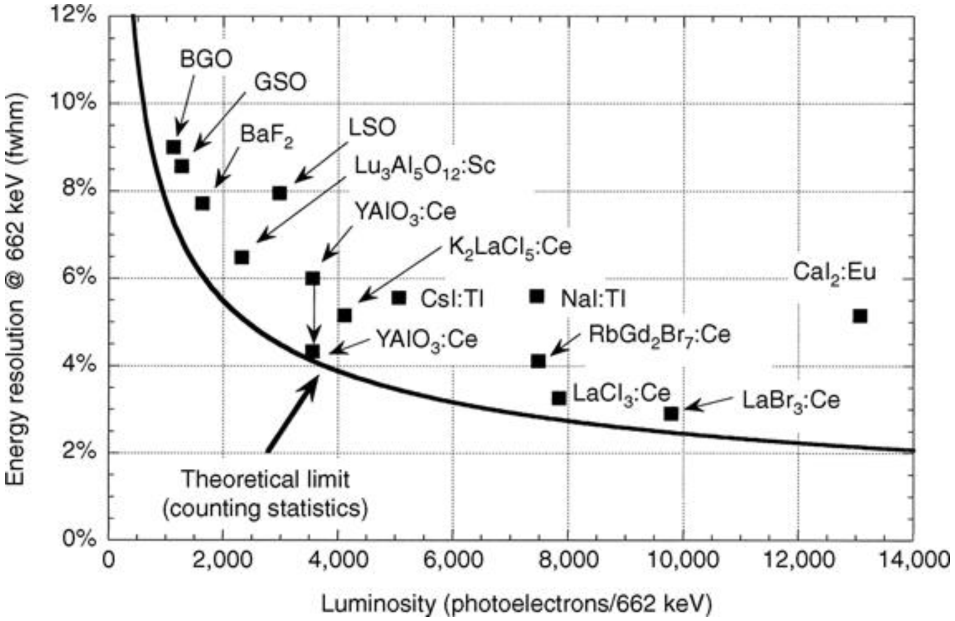
Generally statistical broadening of the photopeak dominates energy resolution *R*.

$$R = K\frac{\sqrt{E}}{E}$$

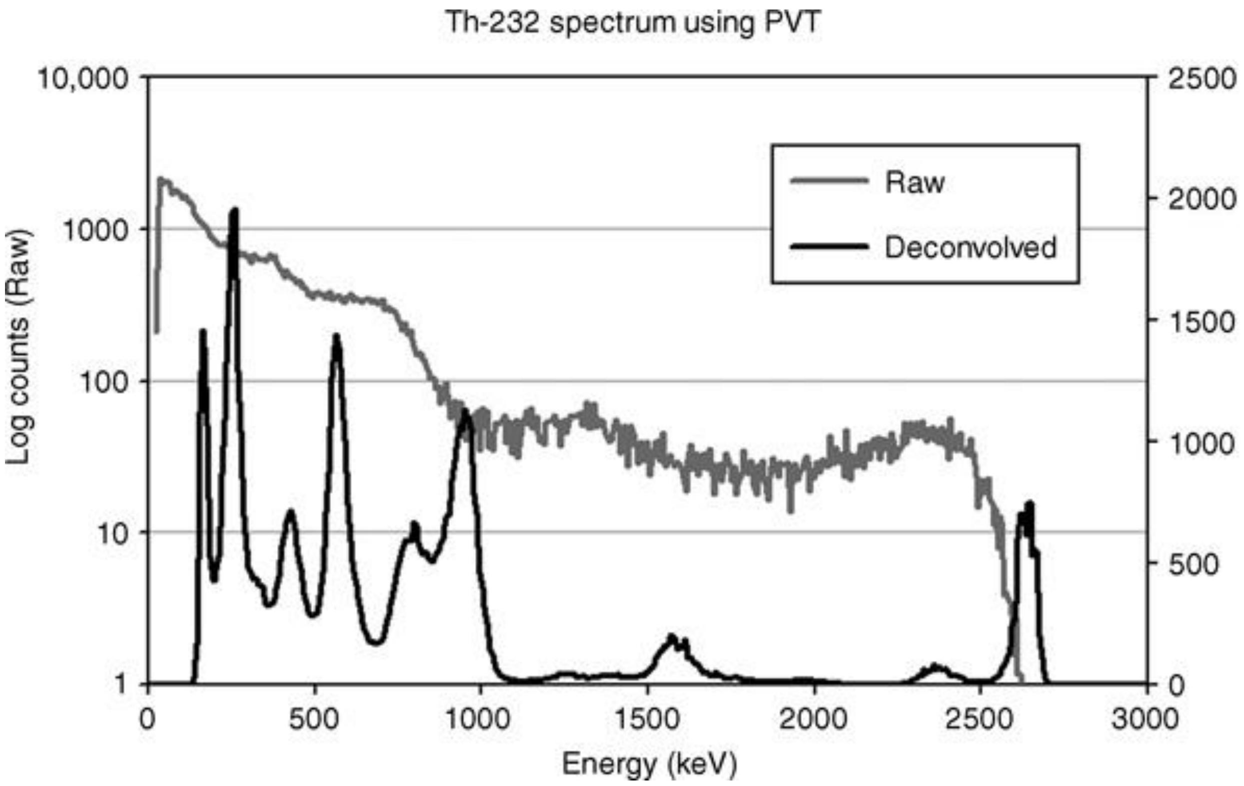
$$\ln R = \ln K - {}^{1}/_{2} \ln E$$

Not quite as steep as predicted by simple assumption of just Poisson statistical effect

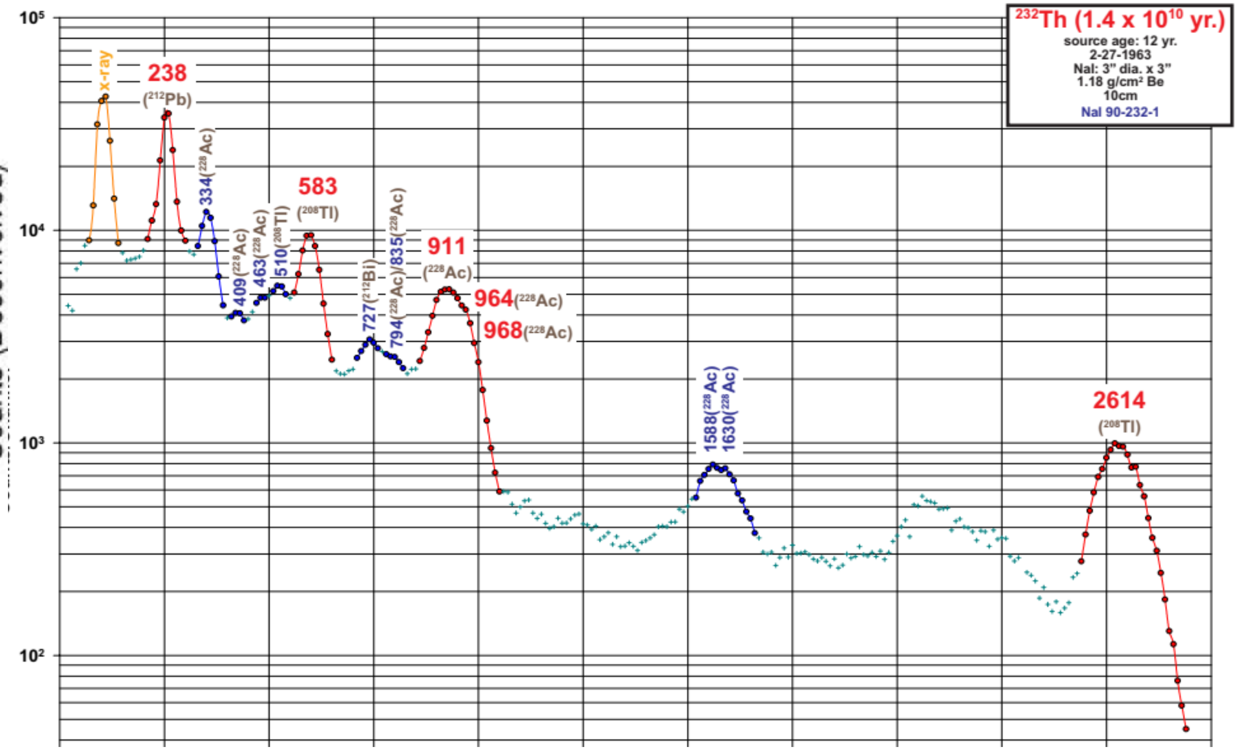




Low Z scintillators, e.g. plastic



Plastic scintillator spectrum



NaI(Tl) spectrum

Positron Emission Tomography

Text

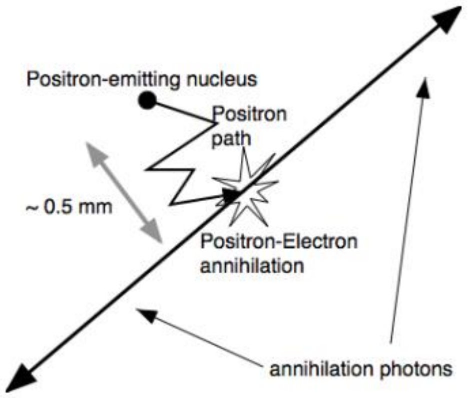


Fig. 1. General principle of PET imaging: decay of radionuclide, positron (β^+) emission, multiple scatter in tissue, annihilation with electron, and production of two back-to-back 511 keV annihilation photons. (Not to scale.)

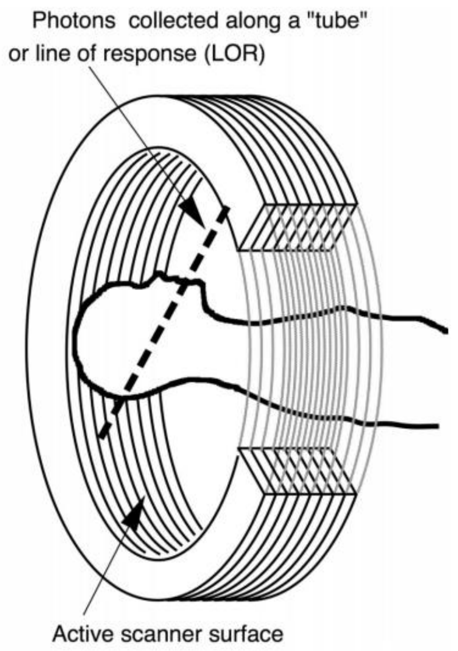


Fig. 3. PET scanner schematic with a possible line-of-response.

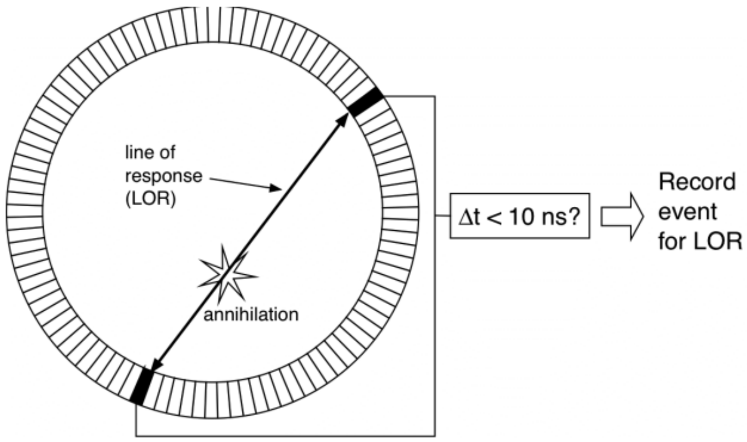


Fig. 4a. Coincidence processing in PET data acquisition.

Scintillators for PET

Need bright scintillators (detecting 511 keV photons) and fast scintillators (time-of-flight).

Table 1. Scintillators used in PET Scanners.

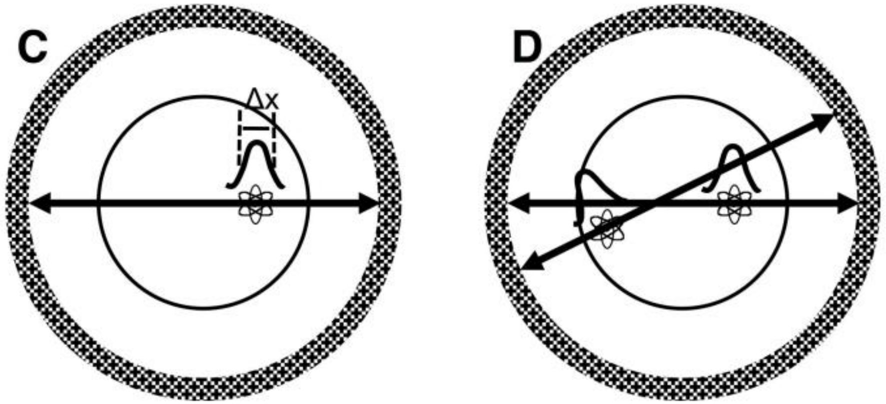
Material	Cost	Light Output[1]	Effective Density[2]	Light Decay Time[3]	Comments
NaI(Tl)	cheap (relatively)	highest	lowest	long	Hygroscopic No longer used
BGO	expensive	lowest	highest	long	Does not support TOF PET
LSO (or LYSO)	more expensive	high	high	very short	Some patent disputes
GSO	more expensive	very high	somewhat lower than LSO	very short	No longer used

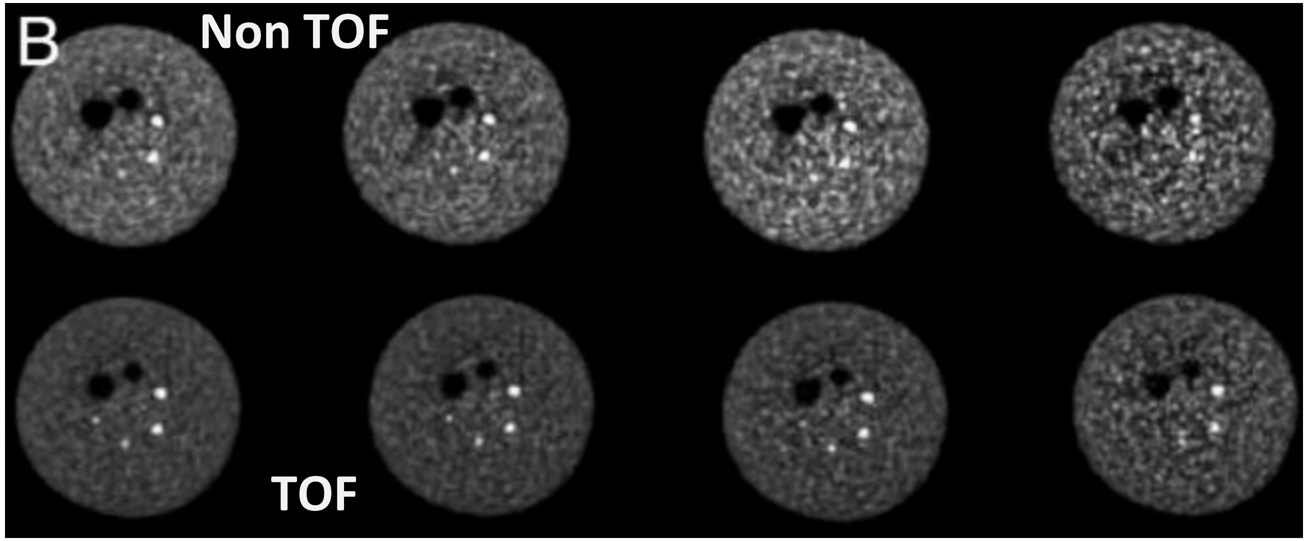
[1] determines energy and spatial resolution
[2] determines scanner sensitivity
[3] determines scanner deadtime and random coincidences rate as well as ability to be used with time-of-flight (TOF) PET imaging

Abbreviations: BGO = bismuth germinate, NaI(Tl) = thalium-doped sodium iodide, LSO = lutetium oxyorthosilicate, LYSO = lutetium yttrium orthosilicate, GSO = gadolinium orthosilicate

Time-of-flight PET

With bright and fast scintillators can measure the difference in arrival times and determine, with some error, the interaction position in depth for every event. This leads to improved contrast, fewer artefacts. If you would like to know more, I recommend *J Nucl Med*. **56** (2015) 98–105. doi:10.2967/jnumed.114.145029





Non-TOF and TOF images for a 35 cm diameter cylindrical lesion phantom for scan times of (left to right) 5, 3, 2, and 1 minutes.